DEVELOPMENT OF SOLDIER CONFORMABLE ANTENNAE USING CONDUCTING POLYMERS

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**ABSTRACT**

A conducting polymer based camouflaged antenna has been developed for use by soldiers in theater. The antenna is built using polypyrrole strips fabricated using a custom built instrument capable of cutting fiber strips with varying widths (20μm-10mm), thicknesses (2 μm-100 μm) and up to 10 m long. These fibers have been woven into a patch form and their radiating properties are studied. We have also demonstrated that this antenna can transmit and receive information at distances up to 2.75 km in an urban environment.

## 1. INTRODUCTION

Soldiers performing dismounted operations in the field use radios that have antennas with a distinct visible signature and can become easy targets. These antennas also tend to snag on other equipment or vegetation creating a hazard and a distraction to any ongoing operation. Therefore it has become necessary to develop an antenna that can conform to soldiers and be virtually indistinguishable from a soldier's body armor. Traditional antenna materials such as metals tend to break under repeated cycles of loading and unloading which makes them undesirable for this application. Existing wearable antenna technologies (SINCGARS - MBITR Wearable Antenna ; Tactical Vest Antenna System™ ) have limited bend radii, are bulky and cannot easily be incorporated into clothing. We propose using conducting polymers materials to create patch antennas that can easily conform to a soldier's body and can match the performance of existing antennas. Antennas based on these materials have reached high enough electrical conductivities such that they have been developed for radio frequency identification (RFID) applications (Kirsch et al., 2009; Cichos et al., 2002). These materials can be developed as a flexible, conformable and even transparent alternatives to traditional metal-based approaches.

Conducting polymers are electrically conducting materials that have high electrical conductivities (~$10^5$ S/m) and are extremely lightweight and flexible. Wires synthesized from these materials have a wide range of applications that can include smart textiles (Carpi and Rossi, 2005; Spinks et al., 2003), neural probes (Cui et al., 2003; George et al., 2005), polymer based actuators (Baughman, 1996; Bar-Cohen, 2004), sensors (Wu et al., 2007; Wiedenman and Hunter, 2008) and antennas (Kirsch et al., 2009). The fabrication technique in (Kirsch et al., 2009) involves an additive printing technique that can print numerous patterns, but with limited inherent conductivity (less than 600 S/m). There is also interest in generating highly electrically conductive polymer fibers that can be directly incorporated into clothing to function as an antenna but a printing technique has to be developed for this process.

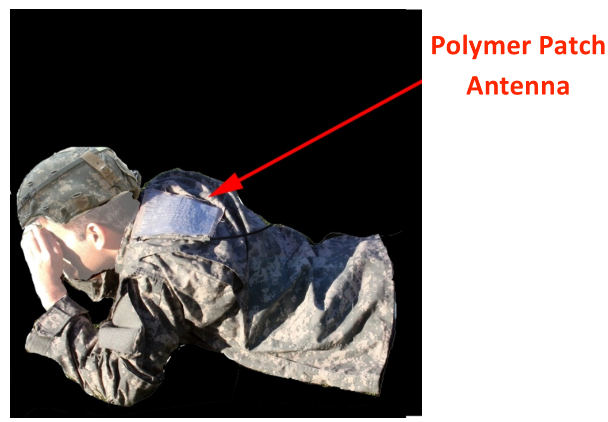


**Fig. 1:** The prototype polymer patch antenna attached to the back of a uniform.

Prior studies have shown wires of conducting polymers can be created using template based fabrication techniques (Carswell et al., 2003; Li et al., 2002; Cepak and Martin, 1999), wire slicing tools (Bae et al., 2008; Ruddy, 2006; Saez et al., 2009), and electrospinning (Ruddy, 2006; Chronakis et al., 2006). Electrochemically deposited thin films of polypyrrole (PPy) are attractive conducting polymer due to their robust mechanical properties and high electrical conductivities ($10^5$ S/m) (Madden et al., 2004b; Madden et al., 2004a; Madden et al., 2002). Due to their relatively high conductivities required for the final wires and the ability to generate large aspect ratios, we have adapted the technique developed by Saez et al to fabricate our antennas. This novel polymer based antenna can easily be adapted to conform to a soldier's body (Fig. 1). We have conducted

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preliminary tests to assess the feasibility of the use of these wires as antenna.

## 2. POLYMER WIRE FABRICATION

Polypyrrole films cannot be synthesized as long wires using traditional electrospinning or wet spinning techniques. The electrochemical deposition process involved in the fabrication of polypyrrole traditionally cannot create fibers, however the thin films generated from this process have high conductivities. We have adapted a new approach to manufacture wires of polypyrrole up to 10 m long having varying cross sections. The pyrrole monomer was vacuum distilled before use. Polypyrrole was electrodeposited on a glassy carbon cylindrical substrate at -40 C at a constant current density of 1.0 $A/m^2$ for 8 hours. The deposition solution used was 0.05 M pyrrole in 0.05 M tetraethyl ammonium hexaflourophosphate in propylene carbonate. The cylindrical glassy carbon substrate is 85 mm tall and 75 mm in diameter. A thin layer of polypyrrole forms on the surface of the electrode approximately 10-20 μm thick. The electrode is then mounted on a custom built instrument (Saez et al., 2009) that slices the wires.

The instrument consists of 4 axes (1 rotary and 3 linear axes) (See Fig. 2) with the electrode mounted on the rotary axis. One of the linear axes consists of a sharp blade that slides along with a rotating crucible. The blade slices the film by running over the crucible in a helical pattern. The blade is simultaneously oscillated along its length such that a fresh cutting edge is continuously presented at the point of contact with the crucible. This instrument has enabled the production of PPy microwires with widths as small as a few micrometers and lengths ranging from tens of millimeters to a few meters. It may also be used to slice microwires from films made of other types of conducting polymers.

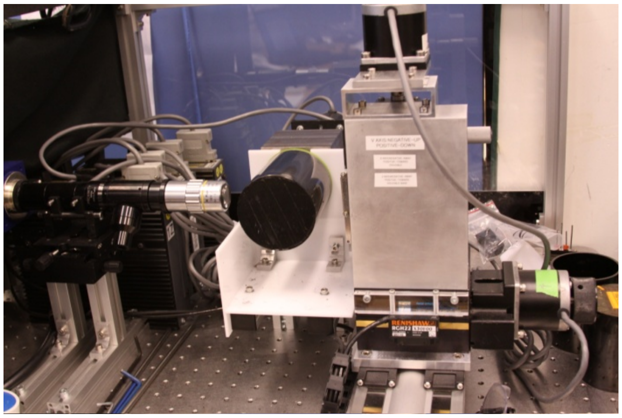

**Fig. 2:** Picture of wire slicing instrument.

These wires are then spooled in a circular spool that can later be used for various applications. The electrical conductivities are measured using a 4-point electrical conductivity probe, and are typically between 6000-10000 S/m. The mechanical properties of the fibers were tested using a uniaxial tensile test and the PPy wires had an average yield stress of 50 MPa, failure force of 150 MPa and final strain of 50 ± 14.8%. The elastic modulus measured from the uniaxial test is on average is 1 GPa.

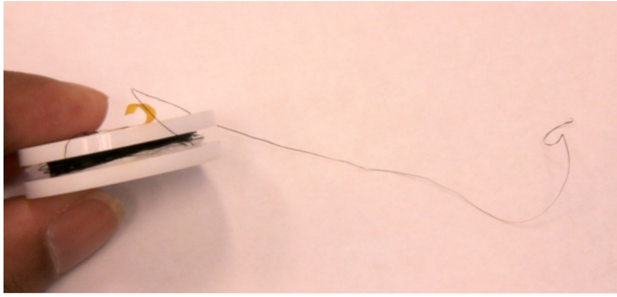

**Fig. 3:** Picture of 5 m long spooled PPy fiber with a 200 μm x 20mm cross-section.

These fibers can range from a few microns to tens of millimeters in width and thickness. The large conductivities and large strengths make these materials ideal candidates for direct incorporation into fabrics.

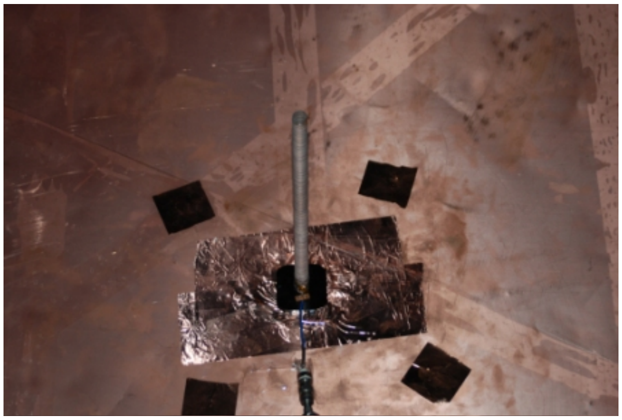

**Fig. 4:** Picture of a helically wound PPy strip around an acrylic pillar. This setup was used to test the effectiveness of the PPY strip as an antenna.

We conducted a preliminary analysis to assess the effectiveness of the polymer material as an antenna (Fig 4). Tests were conducted at 250 MHz and 500 MHz . A -10 dBi attenuation was observed at those frequencies for the PPy strip in the specific geometry tested. This is expected since the PPy is less conductive than a metal.

## 3. PRELIMANARY PROTOTYPE

Current body wearable antenna devices center on devices that are large and that can be incorporated into a vest or backpack. The devices are cumbersome and add unnecessary weight and discomfort to a soldier's suit. On the other hand there have been some advances in building devices that can be incorporated directly into clothing. These devices can be susceptible to long term degradation and loss of performance due to repeated aggressive washing and heating cycles. Our design focuses on an easily removable patch design. This enables the user to easily attach and detach the antenna from their radios while at the same time avoiding the problems associated with repeated cycles of washing. IT also provides a low profile, lightweight, highly flexible design that can easily conform to any active surface. The base design consists of 3 layers: A top camouflage layer made of any type of flexible fabric. An intermediate feed/radiator layer and a bottom isolation/attachment layer (Fig. 5). The feed/radiator layer is uniplanar and can consist of a meander line monopole or a wide-band radiator such as a bow-tie slot radiator that can be optimized for the particular application under consideration. The bottom layer isolates the middle layer from the body and contains attachments such as a hook and loop mechanism that can be used to attach the antenna to a uniform.

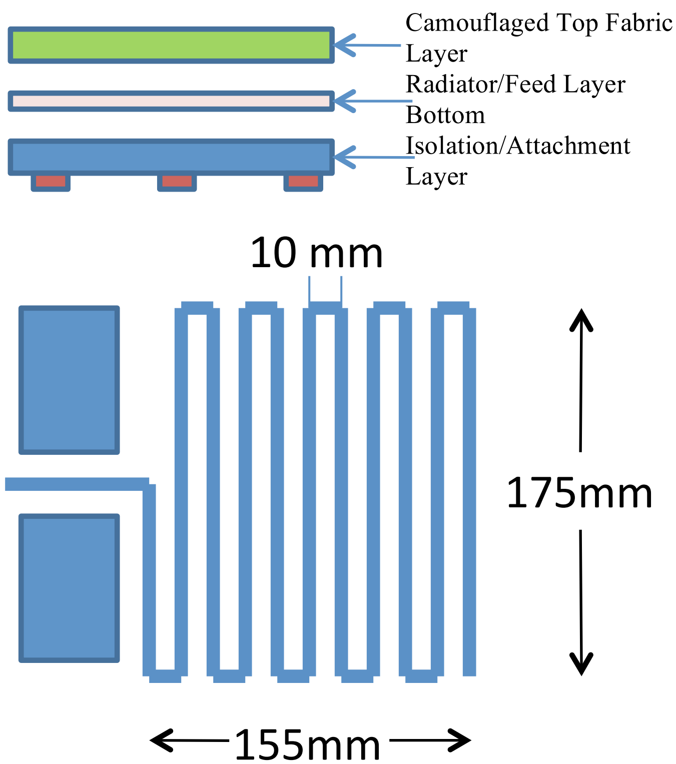


**Fig. 5:** Top) Schematic of our patch antenna design showing the 3 layers. Bottom) Schematic of the PPy strip within the feed layer (figure not to scale) with the ground plane located at the base of the antenna.

We used a meander line monopole (Godara, 2002) with a co-planar waveguide design to create our initial prototype feed layer. A strip of polypyrrole 4 m in length, 1 mm wide and 20 μm thick was cut using the technique described above. It was then manually wound in the desired shape and encased in a non-conductive low dielectric plastic (high density polyethylene, dielectric constant of 2.5) in order to protect it. A ground plane of a strip of polypyrrole was also embedded in the same plastic and manually sewn into the fabric as well. The antenna was designed to have its first resonant frequency at 200 MHz. The resulting laminate was then sewn into a camouflage material. The polymer was then connected to a coaxial cable using a custom build connector that was also sewn into the fabric. The other end was connected to a standard TNC connector (Pictures shown in Fig. 6). The connecting cable is strain relieved within the fabric itself (the bottom attachment layer) to provide additional robustness.

**Fig. 6:** Left) Picture of the prototype polypyrrole antenna with the upper layer peeled off and middle feed layer exposed. Right) The prototype with all the layers along with the TNC connector.

The overall device has dimensions of 200 mm x 200 mm and 1 mm in thickness, along with a very low bend radius as demonstrated in Fig. 7.

**Fig. 7:** The patch antenna device pinched to illustrate the flexibility of the overall design.

The connector cable in the current embodiment of the prototype is directly attached to the patch itself but it is not necessary for this to be the case. A connector can be directly connected to the patch and the device can be directly connected to the relevant radio. Fig. 8 shows one method by which the patch can be connected to a radio with a cable running down the back.

**Fig. 8:** Patch antenna (red box) design shown attached to the shoulder of an army-issued jacket using a hook and loop connector.

## 4. RESULTS

Our patch design was tested to access its viability as an antenna. The measurements were taken with a network analyzer and the radiation patterns were taken in a tapered anechoic chamber free from any outside interference. The chamber was calibrated to a known isotropic radiator. The test antenna was secured in a stable position with the electric field oriented vertically. Fig. 9 shows the 0 dBi normalized radiation patterns of the prototype antenna. The gains of the antennas were calculated at different frequencies. At 200MHz the gain is about 0dBi, at 250MHz the gain is -1dBi and at 500MHz the gain is 8.2dBi. The lower gain is due to the low conductivity of the conducting polymer (8000 S/m) as compared to copper (6x$10^7$ S/m). A noticeable amount of directionality is visible in each tested frequency.

The conductivity of the polymer can be improved by using different dopant ions during the electrochemical deposition process. The return loss (S parameters) of the polymer antenna is shown in Fig 10. At the design frequency of 200 MHz the return loss is -20 dB and it shows a sharp resonant frequency. The bandwidth of the antenna is around 50 MHz is a significant improvement of selectivity's previously reported (Kirsch et al., 2009) for a conducting polymer antenna. Since the antenna was assembled manually there is a slight taper in the meander line geometry that leads to the second resonant peak. Using automated sewing techniques better and more precise geometries can be created that can make these antennas have a better return loss.

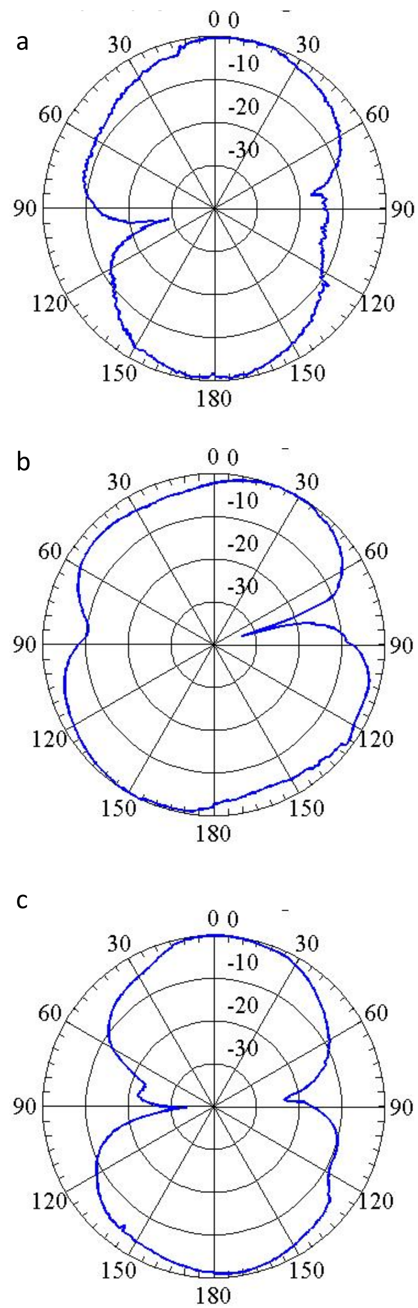


**Fig. 9:** The radiation directivity of our polymer meander line antenna design in the horizontal plane at a) 200 MHz b) 250 MHz c) 500 MHz.

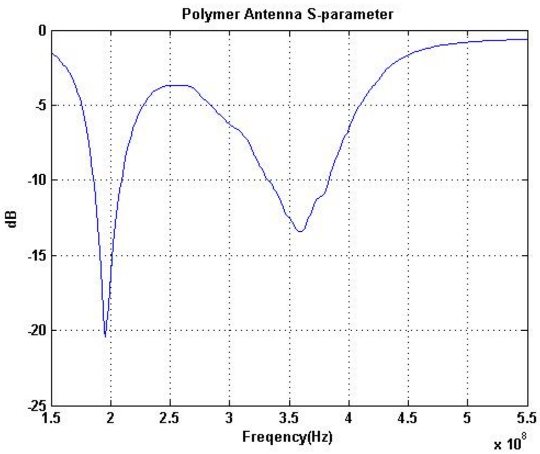


**Fig. 10:** Measured return loss of a conducting polymer antenna.

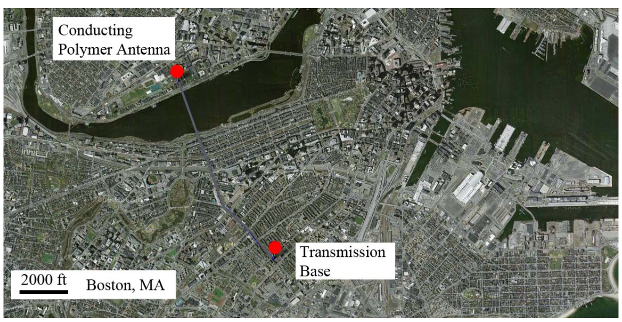


**Fig. 11:** Transmission/reception range of a conducting polymer patch antenna.

As a proof of concept, we have also tested our antenna using commercially available radios. We were able to demonstrate transmission and reception over 2.75 km radius within a downtown urban environment.

## DISCUSSION

Our initial prototype antenna shows that **a** meander line dipole antenna constructed conducting polymer based flexible antenna is a feasible alternative to existing antennas based on metals. We developed a meander line monopole antenna due to the ease of fabrication and analysis. However, other designs such as a meander line dipole, tapered slots or bow-tie geometry can be created using the same technique that can reduce the overall size of the antenna. The electrical conductivity and mechanical robustness of these materials can be improved by blending them with additives such as carbon nanotubes or metal nanoparticles. Incorporating these materials also can increase the strength and lead to higher overall gains over a wider range of frequencies. The strength of the overall antenna design is limited by the type of fabric used to encase the feed layer and using stronger fabrics such as Kevlar can increase the overall strength of the prototype as well.

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